Can the Data from the CERN $p\bar{p}$ Collider Limit Gaugino Masses?

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We show that the hadronic decays of the W gaugino ($\tilde{W}$) and Z gaugino ($\tilde{Z}$) produced via each of the processes $W\to\tilde{W}\tilde{\gamma}$, $W\to\tilde{W}\tilde{Z}$, and $Z^0\to\tilde{W}\bar{\tilde{W}}$ lead to a substantial rate for monojet and dijet+missing p_T at the CERN collider. If the latter two decays are kinematically allowed, one should expect a comparable number of spectacular dilepton and trilepton events with little hadronic activity. In addition, there would also be jet+lepton+missing-p_T signals. Absence of such signals could lead to the most stringent direct experimental limits on $\tilde{W}$ and $\tilde{Z}$ masses currently possible.

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There are several well-known theoretical reasons for considering supersymmetry (SUSY)[1] to be a symmetry of nature, although there is no experimental evidence for the existence of SUSY particles. Electron-positron collider experiments set (direct and indirect) limits on the masses of SUSY particles.[2] Since these are produced in pairs, direct limits of SUSY-particle masses are typically equal to the beam energy (<23 GeV). An exception to this is the limit on the Z-gaugino mass obtained by a study of the reaction $e^+e^-\to\tilde{Z}\tilde{\gamma}$.[3] In addition, there are indirect limits such as the limit on the scalar-electron mass ($\simeq 50$ GeV for $m_{\tilde{\gamma}}\simeq 0$) obtained by Bartha *et al.*[4] Also, a conclusive absence of a sufficient number of missing-p_T ($\not{p}_T$) events at the CERN collider can be translated[5] into lower bounds of $m_{\tilde{q}}\gtrsim 65$–75 GeV ($m_{\tilde{g}}\gtrsim 60$–70 GeV) depending on $m_{\tilde{g}}$ ($m_{\tilde{q}}$).

At this point, it is worth noting that in SUSY models with $m_{\tilde{\gamma}} << m_W$,[6] there are gaugino eigenstates $\tilde{W}$ and $\tilde{Z}$ that have the same quantum numbers as the W and Z bosons, but are lighter than the corresponding gauge bosons.[7] It has already been noted by several authors[8] that it may be possible to produce these states via the decay of the gauge bosons at the CERN collider, i.e., via the processes $W\to\tilde{W}\tilde{\gamma},\tilde{W}\tilde{Z}$ and $Z\to\tilde{W}\bar{\tilde{W}}$. The gauginos subsequently decay via the processes $\tilde{W}\to l\bar{\nu}\tilde{\gamma}$ or $\tilde{W}\to q\bar{Q}\tilde{\gamma}$, and $\tilde{Z}\to l\bar{l}\tilde{\gamma}$ or $\tilde{Z}\to q\bar{q}\tilde{\gamma}$. This leads to characteristic n-jet+m-lepton+$\not{p}_T$ signatures. In this Letter, we study these signals for the case of heavy (~ 100 GeV) scalar quarks[5] and scalar leptons, and examine if gauginos produced by the decay of $W^{\pm}$ and Z^0 would indeed be seen at CERN. The case for $m_{\tilde{W}} > m_{\tilde{l}}$ has been considered by Baer and Tata.[9]

The gaugino–Higgs-fermion mixing angles that determine the eigenstates $\tilde{W}$ and $\tilde{Z}$ depend on three parameters: (i) the Higgs-fermion mixing mass term $2m_1\tilde{h}_1\tilde{h}_2$, (ii) the ratio v_1/v_2 of the vacuum-expectation values of the Higgs fields, and (iii) the soft-SUSY-breaking SU(2) gaugino mass μ_2. The two parameters m_1 and μ_2 can be eliminated in favor of the masses of $\tilde{W}$ and $\tilde{\gamma}$, respectively. For definiteness, we have chosen $v_1/v_2=1$, as required by supergravity models in which the SU(2) ⊗ U(1) breaking is driven[10] by a top quark of mass ~ 40–50 GeV.[11] We have diagonalized the charged sector exactly, whereas the neutral sector has been diagonalized in the approximation $\mu_2 << M_W$ (our analysis is thus restricted to $m_{\tilde{\gamma}}\lesssim 10$ GeV). We may choose $m_{\tilde{W}}$ and $m_{\tilde{\gamma}}$ as free parameters in terms of which $m_{\tilde{Z}}$ and the couplings are determined.[12]

For $m_{\tilde{W}}\lesssim M_W$ and for $m_{\tilde{q}}\simeq m_{\tilde{l}}\gtrsim 100$ GeV, the $\tilde{W}$ branching ratio into each family of leptons is 11% for $m_{\tilde{\gamma}}=0$[13] and is unaltered by the additional mixing induced by a nonzero photino mass of up to 10 GeV. The $\tilde{Z}$ branching fraction into leptons (13% for $m_{\tilde{\gamma}}=0$), however, is quite sensitive to $m_{\tilde{\gamma}}$, particularly for smaller values of $m_{\tilde{Z}}$. For example, for $m_{\tilde{\gamma}}=8$ GeV, it varies from 18% for $m_{\tilde{Z}}=26$ GeV to 14% for $m_{\tilde{Z}}=52$ GeV, independently of the scalar mass.

As we have already mentioned, the characteristic signature of gaugino production is n-jet+m-lepton (e or μ)+$\not{p}_T$ events ($n,m=0,1,2,3$). We emphasize that the monojet and dijet events *must be accompanied by jet(s)+lepton(s)+$\not{p}_T$ events and by multilepton+$\not{p}_T$ events with little hadronic activity.* Moreover, these multilepton events would be essentially free from background.[9] Monojet production from gauginos has also been considered by Chamseddine, Nath, and Arnowitt.[14]

The calculation of the squared matrix elements is quite intractable with usual trace techniques. If we include off-mass-shell W and Z effects, there are three production amplitudes for $\tilde{W}\tilde{\gamma}$, $\tilde{W}\bar{\tilde{W}}$, and $\tilde{W}\tilde{Z}$ for each initial state and three (four) amplitudes for the hadronic decay of the $\tilde{W}$ ($\tilde{Z}$). Even when we assume pole dominance for $q\bar{q}\to\tilde{W}\tilde{Z}$, there are twelve amplitudes for each hadronic final state, and hence 78 often lengthy traces need to be evaluated. The calculation is made manageable by the direct computation of the helicity amplitudes. We have used the formalism of Hagiwara and Zeppenfeld.[15]

In our computation, we impose the following cuts, inspired by the experiment of Arnison *et al.* (UA1 Collaboration):

$$|P_{Te}| \geq 10 \text{ GeV}, \quad |\eta_e| \leq 3.0, \tag{1a}$$

$$|P_{T\mu}| \geq 3 \text{ GeV}, \quad |\eta_\mu| \leq 2.0, \tag{1b}$$

$$|P_{Tj1}| \geq 25 \text{ GeV}, \quad |P_{Tj2}| \geq 12 \text{ GeV}, \quad |\eta_j| \leq 2.5. \tag{1c}$$

Two partons are coalesced if they satisfy the condition $\Delta r \equiv (\Delta\eta^2 + \Delta\phi^2)^{1/2} < 1$. We assume that a muon within the acceptance (1b) will be identified even if it is inside a jet; for electrons in events containing jet activity we have imposed a more stringent p_T cut, i.e., $|P_{Te}| > 15$ GeV. Furthermore, for electrons within $\Delta r = 1$ of any parton, we impose an additional cut

$$|P_{Te}| \gtrsim 4|P_{T\text{parton}}|. \tag{1d}$$

Whenever an electron fails to satisfy the above requirements, we assume that it cannot be distinguished from a hadron, and hence treat it as part of a jet. Finally, for events containing any jet activity, we require a trigger

$$p_T > \text{Max}(15 \text{ GeV}, 4\sigma),$$
$$\sigma = (0.7 \text{ GeV}^{1/2}) \left(\sum_{\text{partons}} E_T + E_T^S \right)^{1/2}, \tag{1e}$$

where E_T^S accounts for soft hadronic debris in large-p_T events, and is distributed according to $4E_T/\langle E_T \rangle^2 \times \exp(-2E_T/\langle E_T \rangle)$ with $\langle E_T \rangle = 45$ GeV.[16] We employ the parton distributions of Duke and Owens[17] (set 1) and a QCD-motivated K factor of 1.4 for W and Z production, and incorporate smearing due to W and Z transverse motion and experimental resolutions as in Baer.[18]

The monojet and dijet cross sections as functions of gaugino mass are shown in Fig. 1 for the case where both the gauginos decay hadronically. We have nominally chosen $m_{\tilde{\gamma}} = 8$ GeV for illustrative purposes. The following features are worth noting. (i) The monojet cross section exceeds 10 pb for $m_{\tilde{W}} \lesssim 55$ GeV. Of course, standard-model backgrounds have to be considered before any conclusions can be drawn.[19] (ii) The monojet-to-dijet ratio varies from ~ 10 for light gauginos to ~ 2 for $m_{\tilde{W}} \simeq 75$ GeV. (iii) The kinks in the curves at $m_{\tilde{W}} = 40$ GeV and $m_{\tilde{W}} = 50$ GeV respectively mark the $W \to \tilde{W}\tilde{Z}$ and $Z \to \tilde{W}\bar{\tilde{W}}$ thresholds. Beyond $m_{\tilde{W}} = 50$ GeV almost all the signal is from $W \to \tilde{W}\tilde{\gamma}$. (iv) For dijets, the turnover occurs

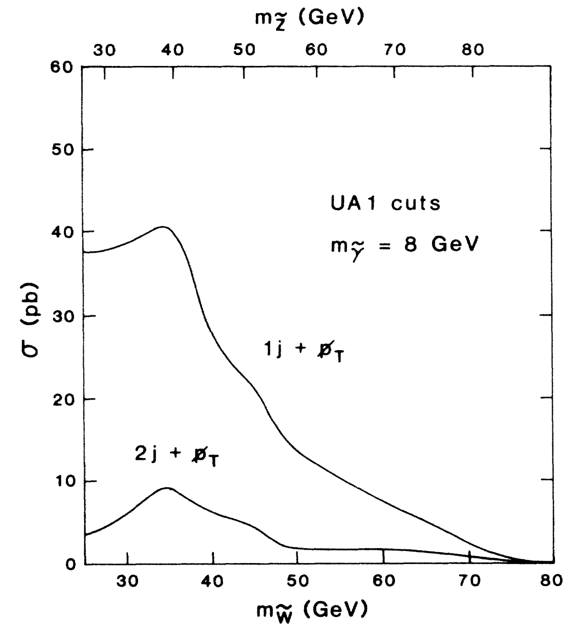

FIG. 1. Expectations for monojet and dijet + $\not{p}_T$ events from $\tilde{W}\tilde{\gamma}$, $\tilde{W}\bar{\tilde{W}}$, and $\tilde{W}\tilde{Z}$ production in $p\bar{p}$ collisions at $\sqrt{s} = 630$ GeV when both gauginos decay hadronically, for $m_{\tilde{q}} = m_{\tilde{l}} = 200$ GeV.

for small $m_{\tilde{W}}$ (and $m_{\tilde{Z}}$) because the quark jets are not hard enough or well enough separated from each other to be identified as two jets. The sudden flattening of the dijet curve beyond $m_{\tilde{W}} = 50$ GeV occurs because almost all the cross section comes from $W \to \tilde{W}\tilde{\gamma}$. As the $\tilde{W}$ gets heavier, the probability that the event gives a dijet signal grows, which compensates for the decrease of the production cross section.

We now turn to the multilepton signals resulting from the leptonic decay of both the gauginos produced via $W \to \tilde{W}\tilde{Z}$ and $Z^0 \to \tilde{W}\bar{\tilde{W}}$. These events have little associated hadronic activity—only that from higher-order QCD corrections to W and Z^0 production. Furthermore, standard-model backgrounds to these multilepton events are small.[9] The trileptons, the like-sign dileptons, and "$e\mu$" pairs would obviously stand out. Also, the e^+e^- and $\mu^+\mu^-$ pairs would be acollinear. We have, therefore, imposed no extra trigger requirement on these signals, which are shown in Fig. 2.

A priori, we may have expected these signals to be small due to suppression by the product of the leptonic branching fractions. However, almost all muons and a substantial fraction of electrons satisfy the acceptance cuts, whereas the $\not{p}_T$ trigger requirement and jet cuts eliminate a large fraction of the nonleptonic signals shown in Fig. 1. In fact, for small enough $\tilde{W}$ masses, the multilepton signal exceeds the jet signal! The following features of Fig. 2 are worth noting. (i) The or-

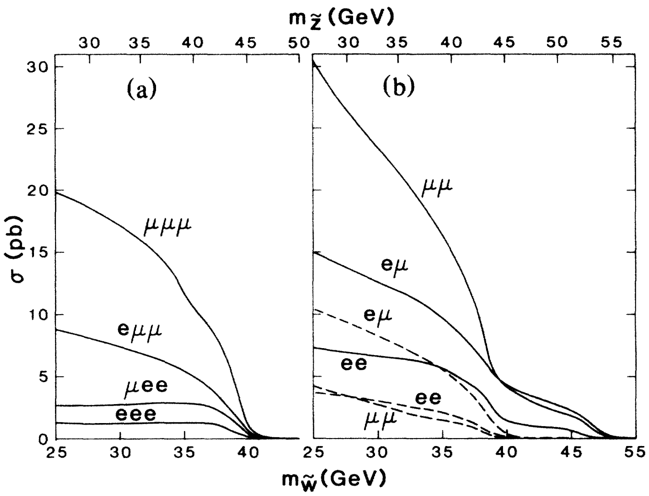

FIG. 2. Multilepton cross sections from $\tilde{W}\bar{\tilde{W}}$ and $\tilde{W}\tilde{Z}$ production, when both gauginos decay leptonically. (a) Trilepton signals and (b) dilepton signals, including both opposite-sign (OS, solid curves) and same-sign (SS, dashed curves) pairs, are given.

dering of the trilepton events is easily understood from the difference in the p_T cut on electrons and muons. (ii) The trilepton cross section drops off monotonically with increasing gaugino mass. This is quite different from the $m_{\tilde{l}} < m_{\tilde{Z}}$ case (Ref. 9), where the trilepton signal decreases for smaller $m_{\tilde{Z}}$ because the decays $\tilde{Z} \to \tilde{l}^{\pm} l^{\mp}$ typically lead to one very soft lepton which fails to pass the cuts. In the present case, both leptons are hard. (iii) The trielectron cross section is almost flat up to the phase-space boundary. The fact that the electrons tend to be harder for larger gaugino mass (and hence more likely to pass the cut) compensates for the reduction in the uncut cross section. The trimuon signals follow the trend of the uncut cross sections since most of the muons pass the cut. (iv) There is an observable level of same-sign (SS) dilepton signals coming from the case where one of the leptons is missed in a trilepton event. The largest of these signals is for the $\mu^- e^- + \mu^+ e^+$ coming from $\tilde{Z} \to e^+ e^- \tilde{\gamma}$, $\tilde{W} \to \mu\nu\tilde{\gamma}$, because one of the electrons can easily escape the acceptance. Compared to the $m_{\tilde{l}} < m_{\tilde{W}}, m_{\tilde{Z}}$ case,[9] many more $\mu^-\mu^-$ pairs pass the cuts. (v) Opposite-sign (OS) $e\mu$ pairs from $\tilde{W}\tilde{Z}$ production number the same as SS $e\mu$ pairs. $\tilde{W}$-pair production, however, contributes to the OS signal; its contribution is between a quarter and a third of the total signal until the threshold for the $W \to \tilde{W}\tilde{Z}$ is approached when $\tilde{W}$-pair production dominates. (vi) OS ee and $\mu\mu$ pairs come from both $\tilde{W}\tilde{Z}$ and $\tilde{W}\bar{\tilde{W}}$ production. Again, the kink marks the $\tilde{W}\tilde{Z}$ threshold. Standard model backgrounds to these have been analyzed in Ref. 17.

Finally, we consider the case where one of the gauginos decays leptonically, and the other hadronically. This leads to the n-jet + m-lepton + $\not{p}_T$ signals mentioned earlier. We impose the $\not{p}_T$ trigger (1e) for these signals. Shown in Fig. 3 are the rates for these topologies where the cross section, after acceptance cuts, exceeds 0.5 pb. We make the following remarks. (i) The $\tilde{W}\bar{\tilde{W}}$ and $\tilde{W}\tilde{Z}$ reactions both give substantial and almost equal contribution to the monojet rate. There is also a small contribution to the dijet cross section. (ii) For the mixed topology, the largest signal is $\mu + 1$ jet + $\not{p}_T$. Most of these events come from the μ decay of the $\tilde{W}$, since the muonic decay of the $\tilde{Z}$ produces two muons. The reaction $Z^0 \to \tilde{W}\bar{\tilde{W}}$ gives more than half this signal even below the $W \to \tilde{W}\tilde{Z}$ threshold. The $2\mu + 1$ jet + p_T signal may be observable and results from $Z \to \mu\bar{\mu}\tilde{\gamma}$ and $\tilde{W} \to$ jets from the $\tilde{W}\tilde{Z}$ reaction. (iii) Finally, the $\tilde{W}\tilde{Z}$ reaction also gives dimuons from $\tilde{Z} \to \mu\bar{\mu}\tilde{\gamma}$ and $\tilde{W} \to$ hadrons when the hadronic system fails to satisfy the criterion (1c) or (1e). We have kept these dimuon events separate from Fig. 2 because in this case we expect substantial hadronic activity accompanying the dimuons. The dielectron events from this source occur at a negligible rate.

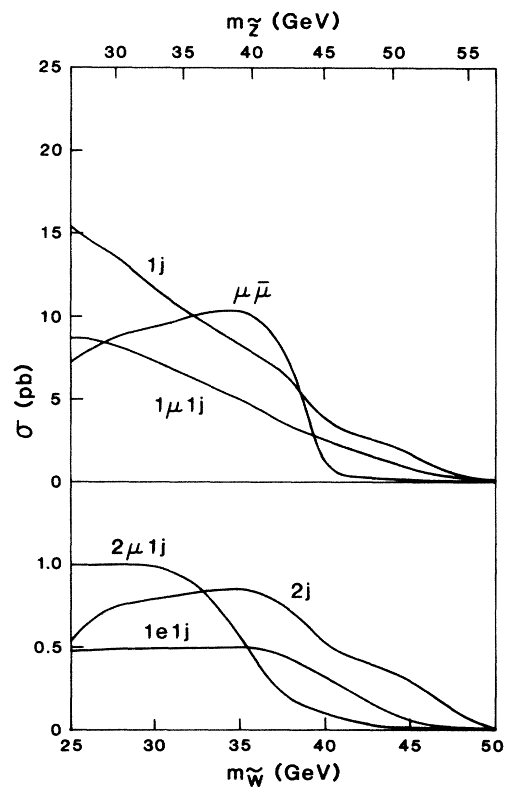

FIG. 3. Largest n-jet + m-lepton + $\not{p}_T$ signals from $\tilde{W}\bar{\tilde{W}}$ and $\tilde{W}\tilde{Z}$ production, where one gaugino decays hadronically and one leptonically. Other signals are also present, but at much smaller levels.

In summary, we have examined the various signals expected from the decays of the gauginos produced via $W \to \tilde{W}\tilde{\gamma}$, $W \to \tilde{W}\tilde{Z}$, and $Z^0 \to \tilde{W}\bar{\tilde{W}}$ at the CERN $p\bar{p}$ collider. We have shown that the hadronic decays of the gauginos lead to a substantial rate of monojet and dijet events at the CERN collider. We have emphasized that if the latter two decays of the W and Z^0 are kinematically allowed, these monojet (dijet) events *must* be accompanied by a variety of spectacular dilepton and trilepton signals that are essentially free from standard-model background. A handful of these events may already be expected in the accumulated CERN data. In addition, there is an observable rate for μ + jet + $\not{p}_T$ events. Absence of such signals may make it possible for the UA1 and UA2 Collaborations to conclude already at least that the decay $W \to \tilde{W}\tilde{Z}$ is kinematically suppressed, corresponding to $M_{\tilde{W}} > 36$– 38 GeV and $M_{\tilde{Z}} > 42$–44 GeV depending on variations in $M_{\tilde{\gamma}} = 0$–10 GeV. This would correspond to about 35 pb of jet + $\not{p}_T$ events, and 25–30 pb of multilepton events, which even after efficiency corrections should leave an observable signal. Details of the relevant distributions and expectations for the Fermilab Tevatron Collider will be discussed in a forthcoming paper.[12]

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